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# Universal drying rate constant of seedless grapes: A review

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ABSTRACT

Drying kinetics of materials may be described completely using their transport properties together with those of the drying medium. In the case of food drying, the drying rate constant '*k*' was used instead of transport properties. The drying rate constant combines all the transport properties and may be defined by the thin layer equation. A large number of investigators have worked on solar drying of grapes and the drying rate constant has been calculated through conditions of drying product temperature, equilibrium relative humidity, equilibrium moisture content and drying time. Several mathematical models have been proposed to describe the moisture movement in the drying product. Among the thin layer models, the exponential model is found to be simple and most suitable to describe drying characteristics of grapes. The exponential model considers only the surface resistance, implying that all the resistance is concentrated in a layer at the surface of the drying product. Drying characteristics obtained from experimental results of some investigators were taken into consideration to estimate the value of drying rate constant for grapes. The best fit for drying rate constant value was selected from among the various drying curves obtained experimentally by investigators till date.



**Contents**



## 1. Introduction

Drying is quite a simple ancient skill. It is one of the easily accessible and the most widespread processing technology [1]. Drying grapes either by open sun drying, shade drying or mechanical drying produces raisins [2]. Historically, production of raisins from grapes can be traced back to 1490 BC in Greece [3].

There are sixty one countries in the world which grow grapes to a sizeable extent as per the final data of 2009 available on the website of Food and Agriculture Organization. The annual yield of grapes in India during 2009 was 1,878,000 MT [4] and the major grape growing states are Maharashtra, Karnataka, Punjab, Andhra Pradesh and Tamil Nadu [5].

There are different varieties of grapes grown in India that are used for specific purposes. They are used in wine making, raisin making and for table purpose. The raisin purpose varieties are—Thompson seedless, Manik chaman, Sonaka, Black corinth, Black monukka, Arkavati, and Dattier [6].

Traditional drying methods are successfully employed in almost all grape producing countries. There has been notable improvement in the traditional methods of drying grapes, but the quality of raisin produced is unable to meet the international market standards. In

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order to improve the quality of raisins, industrial dryers such as solar and hot air dryers were introduced. The main disadvantage of solar dryer is the availability of solar radiation for a limited period of time. The use of mechanical industrial dryers has been restricted due to the high fuel and electrical energy costs. It is also not economically viable to develop industrial dryers only for the sake of grape drying as they have a very short harvest period. The grapes before drying are treated with certain chemical solutions to enhance the drying rate. The drying time required for natural grapes is 20 days [7] and for pretreated grapes is 8–10 days [8].

Drying rate constant describes the mechanisms of heat and mass transport phenomena and investigates the influence that certain process variables exert on moisture removal processes. It forms the most essential constant of the actual mathematical model of any dehydration operation, which seeks a proper estimation of the drying time as well as the behavior of all corresponding operational factors playing an important role in the design and optimization of dryers. Drying rate constant is measured through experimental studies of material moisture content removal versus time at various drying conditions. The measurement of material moisture content as a function of time under constant drying air conditions constitutes the so-called drying curve [9]. Drying rate constant data in literature is scarce because of the following factors:

- variation in composition of the material,
- variation of the experimental conditions.

Many investigators have carried out extensive work on solar drying of grapes and some of them have obtained the drying rate constant value for grapes from their experimental results. The drying curves plotted from their experimental results have been considered in this paper to obtain the best curve fit using the Curve Expert Version 1.3 software adopting non-linear regression technique.

## 2. Solar drying of grapes

In solar drying, solar energy is used as either the sole source of the required heat or as a supplementary source [10]. Solar drying of grapes is achieved by different processes using a variety of solar dryers. The open sun drying method practiced since a very long time as well as the natural rack dryers have their own disadvantages and limitations. Many investigators have designed and developed their own solar dryer models for drying grapes. Their published experimental results have shown that the use of solar energy for drying of grapes is economically viable. Detailed studies have proved the superiority of solar dried grapes over naturally dried grapes [11,12]. Some investigators have designed and developed solar dryers working in different modes for making raisins [13–17]. Results published by certain investigators after carrying out drying experiments on grapes using solar dryers designed and developed by them are tabulated in Table 1. It is observed that parameters chosen by each one of them are different, initial moisture content of grapes is varying and final moisture content chosen is also different. The drying temperature selected and air velocities used are also different.

## 3. Laboratory scale hot air dryers used for grape drying

Hot air dryers provide fast and uniform drying under hygienic conditions, which makes them suitable for industrial food drying processes. Restricted availability of solar radiation for 8–9 h has compelled many investigators working on solar dryers to opt for hot air dryers during the preliminary stages of their experimentation. Various types of laboratory scale hot air dryers have been designed, developed and tested by investigators according to their requirement. The type of fuel or energy utilized to generate hot air is mostly dependent on the local conditions. Results published by some investigators after carrying out drying experiments on

**Table 1**
List of investigators with details of experiment carried out on grapes using solar dryer.

| Sl. no. | Name of investigators | Type of dryer | Moisture content | Temperature | Air velocity | Time duration | Reference |
|---|---|---|---|---|---|---|---|
| 1 | Fadhel, Kooli, Farhat, Bellghith, 2005 | Natural convection solar dryer | 80% removed | 20–45 °C | Natural | 4 days | [2] |
| 2 | Fuller and Charters, 1996 | Solar tunnel dryer | Initial-76%; Final-13% | 10–60 °C | Not mentioned | 12 days | [7] |
| 3 | Lutz, Muhlbauer, Muller, Reisinger, 1987 | Solar tunnel dryer | Initial-74–78%; Final-18% | 25–60 °C | 1.5 m/s and 3 m/s | 4–5days | [18] |
| 4 | Goswami, Lavania, Shahbazi, Masood, 1990 | Geodesic dome type solar dryer | 70% removed | 40 °F above ambient | Natural | 10 days | [19] |
| 5 | Tiris Cigdem, Necdet Ozbalta, Mustafa Tiris, Ibrahim Dincer, 1994, 1995, 1996 | Forced convection solar dryer | Not mentioned | 30–60 °C | Not mentioned | 5 days | [20–22] |
| 6 | Halak H., Hilal J., Hilal F., Rahhal R., 1996 | Direct type natural convection solar dryer | Initial-Not mentioned; Final-14% | Not Mentioned | 1.5 $m^3$/min | 3 days | [23] |
| 7 | Mahmutoglu Teslime, Ferhunde Emir and Birol Saygi Y., 1996 | Solar tunnel dryer | Initial-Not mentioned; Final-18% | 50 °C | Not mentioned | 120 h | [24] |
| 8 | Yaldiz Osman, Can Ertekin, Ibrahim Uzun H., 2001 | Forced convection solar dryer | Initial-2.6–3.3 kg water/kg dry matter; Final-0.16 kg water/kg dry matter | 32.4–40.3 °C | 1.5 m/s; 1.0 m/s; 0.5 m/s | 82 h; 66 h; 58 h | [25] |
| 9 | Pangavhane R. Dilip, Sawhney R.L., Sarsavadia P.N., 2002 | Indirect natural convection solar dryer | Initial-349.59% db; Final-17% d.b | 51.9–64.6 °C | Not mentioned | 4 days | [26] |
| 10 | El-Sebaii.A.A., Abdul-Enein S., M.R.I. Ramdan and H.G. El-Gohary, 2002 | Indirect natural convection solar dryer with storage | Initial-Not mentioned; Final-18% | 45.5–55.5 °C | Not mentioned | 60 h | [27] |
| 11 | Abene A., Dubois V., Le Ray M., Ouagued A., 2004 | Forced convection solar dryer with obstacle type-TL | Not mentioned | Not mentioned | 31.3 $m^3/hm^2$ | 5 h 50 m | [28] |
| 12 | Al-Juamily, Khalifa, Yassen, 2007 | Forced convection solar dryer | Initial-84%; Final-20% | 50–64 °C | 0.4 m/s | 3.5 days | [29] |
| 13 | Barnwal and Tiwari, 2008 | Greenhouse type solar dryer | Not mentioned | 25–50 °C | 3.6–4.2 m/s | 17 days | [30] |
| 14 | Rathore and Panwar, 2010 | Solar tunnel dryer | Initial-85%; Final-16% | 45–60 °C | Not mentioned | 7 days | [31] |

**Table 2**
List of investigators with details of experiment carried out on grapes using laboratory scale dryer.

| Sl. no. | Name of investigators | Type of dryer | Moisture content | Temperature (°C) | Air velocity | Time duration (h) | Reference |
|---|---|---|---|---|---|---|---|
| 1 | Karathanos V.T. and Belessiotis V.G., 1997 | Laboratory scale forced hot air dryer | Initial-78%; Final-15% | 60 | 0.5–1.5m/s | 56 | [12] |
| 2 | Saravacos G.D., Marousis S.N. and Raouzeos G.S., 1988 | Laboratory scale tunnel dryer | Initial-2.5–3.3 kg water/kg dry solids; Final-0.8 kg water/kg dry solids. | 60 | 2 m/s | 16 | [32] |
| 3 | Pangavhane D.R., Sawhney R.L., Sarsavadia P.N., 1999 | Laboratory scale dryer | Not mentioned | 60 | 0.5 m/s | 30 | [33] |
| 4 | Marisa Di Matteo, Luciano Cinquanta, Gianni Galiero, Silvestro Crescitelli, 2000 | Laboratory scale convection oven | Initial-84%; Final-20% | 50 | 0.5 m/s | 35 | [34] |
| 5 | Azzouz S, Guizani A, Jomaa W, Belghith A., 2002 | Laboratory scale convective dryer | Not mentioned | 50–70 | 1–2.3 m/s | 17 | [35] |
| 6 | Doymaz I., Pala M., 2002 | Laboratory scale forced hot air dryer | Initial-77.3 to 80.5%; Final-0.2 kg/ kg dry mass | 60 | 1.2 m/s | 22 | [36] |
| 7 | Hamdy H. El-Ghetany, 2006 | Laboratory scale forced hot air dryer | Initial-Not mentioned; Final-35% | 75 | Not mentioned | 6 | [37] |
| 8 | Vania Regina Nicoletti Telis, Vania Araujo Lourencon, Ana Lucia Gabas and Javier Telis-Romero, 2006 | Laboratory scale convective tray dryer | Initial-84%; Final-14% | 50 | 1 m/s | 96 | [38] |
| 9 | Mohsen Esmaiili, Rahmat soutudeh-Gharebagh, Mohammad A.E. Mousavi, 2007 | Laboratory scale convective tray dryer | Initial-3.25 kg water/kg dry matter; Final-0.17 kg water/kg dry matter | 40–70 | 1 m/s | 110 | [39] |
| 10 | Hong-Wei Xiao, Chang-Le Pang, Li-Hong Wang, Jun-Wen Bai, Wen-Xia Yang, Zhen-Jiang Gao, 2010 | Laboratory scale hot-air impingement dryer | Initial–4.24 kg/ kg dry basis; Final-0.25 kg/kg dry basis | 60 | 5 m/s | 37 | [40] |

grapes using a laboratory scale hot air dryer with different temperatures and air velocities are tabulated in Table 2.

## 4. Drying characteristics

The drying characteristic is a plot of moisture ratio versus drying time. Some of the drying characteristic curves which can be plotted are:

- Moisture content of grapes '$M$' versus time '$t$'.
- Drying rate '$dM/dt$' versus time '$t$'.
- Drying rate '$dM/dt$' versus moisture content '$M$' [41].

From the drying characteristics it is observed that, initially there is a constant drying rate that terminates at the critical moisture content and this is followed by a falling drying rate.

Initially the drying of grapes is very rapid because the surface of the product behaves like a water surface and hence drying occurs under the constant rate period. However, after that, drying occurs under a falling rate period and hence, the drying rate is considerably lower. Apart from the initial moisture content of the product, thickness of the grape surface also plays a major role in determining the drying rate [42].

The drying rate decreases continuously with time and decreasing moisture content. The drying rate period is not found to be constant. The total drying process occurring during the falling rate period and the predominant mechanism of mass transfer is that of internal mass transfer. The internal mass transfer is due to liquid diffusion in the interior region of grape and water gets evaporated as it reaches the surface. The most probable mechanism governing moisture transfer is that of liquid diffusion [43].

The drying kinetics of materials may be described completely using their transport properties together with those of the drying medium. In case of food drying, the drying rate constant '$k$' is used instead of transport properties. The drying rate constant combines all the transport properties and may be defined by the thin layer equation. Thin layer equations describe the drying phenomena in a unified manner, regardless of the controlling mechanism. They have been used to estimate drying times of several products and to generalize drying curves.

## 5. Mathematical model

The drying rate should be proportional to the difference in moisture content between the material to be dried and the equilibrium moisture content [44].

Drying rate may be expressed as the thin layer drying equation

$$\frac{dM}{dt} = -k(M_t - M_e) \tag{1}$$

Where $M_e$ is the equilibrium moisture content and $M_t$ is the moisture content at any time $t$.

The moisture content in the product to be dried at any time '$t$' is given by

$$M_t = \left[\frac{(W_i - W_d)}{W_d}\right] \tag{2}$$

where $W_{ti}$ is the initial weight and $W_d$ is the final weight [45].

Several mathematical models have been proposed by investigators describing the moisture movement in various agricultural products. The process of moisture removal from the drying product may be treated similar to the convective heat loss from hot bodies. Liquid or vapor diffusion was assumed to be the primary mass transfer mechanism in drying of grapes. The most widely investigated theoretical model in the thin layer drying of various foods is given by the solution of Fick's second law

$$\frac{\partial M}{\partial t} = \nabla(D_{eff} \nabla M) \tag{3}$$

[46] with the assumptions that

- The principal driving force for mass transport is the internal moisture gradient.
- Temperature within the fruit is constant.
- Either liquid or vapor diffusion predominates [46].

Dimensions of the grapes suggested that they can be treated in spherical coordinates. Solution of Eq. (3), for constant diffusion coefficient, after making a number of simplifying assumptions (constant diffusivity and no shrinkage) and with suitable boundary conditions, for spherical coordinates gives

$$\frac{M_t - M_e}{M_i - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n^2\pi^2\frac{D_{eff}t}{R^2}\right) \tag{4}$$

The values of equilibrium moisture content $M_e$, are relatively small compared to $M_t$ or $M_i$ [47].

So the term $(M_t-M_e)/(M_i-M_e)$ in Eq. (4) gets reduced to $M_t/M_i$; where $M_i$ is the initial moisture content.

For the term $(D_{eff}t/R^2)$ larger than 0.1, the first term of the series solution Eq. (4) can be used.

Consequently, Eq. (4) can be further simplified to a straight line equation

$$\log_{10}\frac{M_t}{M_i} = \log_{10}\left(\frac{6}{\pi^2}\right)\left(-\frac{\pi^2 D_{eff}t}{2.3R^2}\right) \tag{5}$$

Eq. (5) can also be written in a more simplified form as $M_t/M_i = a\exp(-kt)$ or

$$\text{Moisture ratio} = MR = a\exp(-kt) \tag{6}$$

Eq. (6) is known to be the exponential equation. The exponential model, which is considered to be the simplest model to describe the moisture movement in dried products, assumes negligible internal resistance, which means no resistance to moisture movement from within the material to its surface. It considers only the surface resistance, implying that all the resistance is concentrated in a layer at the surface of the material [44]. The exponential model appears to be the most suitable one describing the drying characteristics of seedless grapes.

## 6. Drying characteristics of grapes published by investigators

Many investigators have carried out drying experiments using solar dryers and laboratory scale hot air dryers, some of them have published the drying characteristics of grapes from their experimental results. One drying curve each, from among their published work was chosen by us for analysis in this paper (Figs. 1–10). Contributions of the following investigators were considered—Mahmutoglu et al., 1996 [24], Yaldiz et al., 2001 [25], El-Sebaii et al., 2002 [27], Saravacos et al., 1988 [32], Pangavhane et al., 1999 [33], Azzouz et al., 2002 [35], Doymaz and Pala, 2002 [36], El-Ghetany, 2006 [37], Telis et al., 2006 [38], Esmaiili et al., 2007 [39].

Drying characteristics at a temperature of 60 °C was chosen from the experimental results of Saravacos, Pangavhane, Azzouz and Doymaz with different values of air velocities. Temperature of 50 °C was chosen from the results of Mahmutoglu and Telis. Experimental result of Yaldiz at 39.6 °C was chosen, while the contributions from El-Sebaii, Esmaiili and El-Ghetany did not have the drying air temperature and velocity mentioned. All investigators had adopted different chemical pretreatments prior to drying and the dryers used by each one of them were different.

## 7. Realisation of drying rate constant values-by curve fitting

Values of moisture ratio and drying time in hours obtained from the drying characteristics were fitted into the exponential model using Curve Expert Version 1.3. Non-linear regression analysis was carried out and estimates of the model parameters were obtained. Statistical results such as correlation coefficient ($R^2$) was observed to be greater than the acceptable value of 0.99 and standard error ($\chi^2$) values were found to be low. Hence, it could be concluded that the exponential model would provide a better prediction of the drying characteristics of seedless grapes.

The exponential model equation $y = ae^{(kt)}$ was used and the value of parameters '$a$', '$k$' as well as correlation coefficient and standard error obtained are tabulated in Table 3.

High values of correlation coefficient and low values of standard error indicate that the exponential model satisfactorily describes the drying characteristics of seedless grapes.

Equation $MR = a\exp(-kt)$ can be written as $\log MR = -kt + a$. The plot of log $MR$ versus time is a straight line and slope of the straight line yields drying rate constant '$k$'. The values of log $MR$ and drying time '$t$' were fitted into the linear model using Curve Expert Version 1.3, the parameter '$k$', correlation coefficient and standard error values obtained are tabulated in Table 4.

High values of correlation coefficient and low values of standard error indicate the suitability of the linear model in estimating the value of drying rate constant. Drying rate constant value for grapes from Table 4 was found to be varying from 0.01147 to 0.07212 $h^{-1}$. Variation in the values of drying rate constant can be attributed to variation in the type and quality of grapes used for drying as well as variation in drying air temperature, velocity and relative humidity. The drying rate constant for grapes practically obtained by some of the investigators as mentioned in their publications are presented in Table 5.

The drying rate constant values published by some investigators shown in Table 5 are almost similar and quite close to the values obtained by us after curve fitting using Curve Expert Version 1.3.

Krokida et al., 2004, reviewed the drying rate constant values of more than 35 food materials classified in eight food categories. After having reviewed the data of three authors who had published their experimental results on grape drying, the value of drying rate constant '$k$' was found to be between 0.01 and 0.04 $min^{-1}$ with drying air temperature of 60 °C, drying air velocity 0.6–3 m/s and relative humidity in the range 11–25% [9].

**Table 3**
Parameters of exponential model obtained by non-linear regression analysis for thin layer drying of grapes.

| Sl. no. | Name of investigator | Value of '$a$' | Value of '$k$' | Value of $R^2$ | Value of $\chi^2$ | Model used | Reference |
|---|---|---|---|---|---|---|---|
| 1 | Mahmutoglu | 0.9990298 | −0.02745988 | 0.9999395 | 0.0045278 | Exponential fit Equation $y = a\,e^{(kt)}$ | [24] |
| 2 | Yaldiz | 1.016385 | −0.057986686 | 0.9985760 | 0.0200155 | | [25] |
| 3 | El-Sebaii | 1.0024169 | −0.14605579 | 0.9999312 | 0.0023820 | | [27] |
| 4 | Saravacos | 0.99430927 | −0.082279419 | 0.9987530 | 0.0116937 | | [32] |
| 5 | Pangavhane | 1.018478 | −0.088790556 | 0.9980549 | 0.0239172 | | [33] |
| 6 | Azzouz | 0.97586998 | −0.10544266 | 0.9986957 | 0.0165862 | | [35] |
| 7 | Doymaz | 1.0202164 | −0.13233205 | 0.9968655 | 0.0316734 | | [36] |
| 8 | El-Ghetany | 1.0010088 | −0.16105178 | 0.9999419 | 0.0023357 | | [37] |
| 9 | Telis | 1.0105125 | −0.02426515 | 0.9984802 | 0.0212811 | | [38] |
| 10 | Esmaiili | 1.0419232 | −0.12457296 | 0.9932988 | 0.0430222 | | [39] |

**Table 4**
Drying rate constant and statistical parameters obtained after fitting log MR versus time in a linear model.

| Sl. no. | Name of investigator | Models used by investigator | Proposed model | Value of $k$ ($h^{-1}$) | Value of $R^2$ | Value of $\chi^2$ | Reference |
|---|---|---|---|---|---|---|---|
| 1 | Doymaz | Page/exponential | Exponential model | 0.07212 | 0.9957237 | 0.0601076 | [36] |
| 2 | El-Ghetany | Exponential | | 0.07015 | 0.9996765 | 0.0037511 | [37] |
| 3 | Esmaiili | Not mentioned | | 0.06900 | 0.9879391 | 0.0782326 | [39] |
| 4 | El-Sebaii | Not mentioned | | 0.06335 | 0.9996038 | 0.0037491 | [27] |
| 5 | Pangavhane | Page | | 0.04371 | 0.9977860 | 0.0344757 | [33] |
| 6 | Azzouz | Page | | 0.04340 | 0.9974119 | 0.0222266 | [35] |
| 7 | Saravacos | Not mentioned | | 0.03485 | 0.9990489 | 0.0079335 | [32] |
| 8 | Yaldiz | Two term exponential | | 0.02516 | 0.9940930 | 0.0625351 | [25] |
| 9 | Telis | Page | | 0.01194 | 0.9937898 | 0.0522367 | [38] |
| 10 | Mahmutoglu | Page/exponential | | 0.01147 | 0.9987737 | 0.0288883 | [24] |

**Table 5**
Drying rate constant value for grapes published by investigators.

| Sl. no. | Name of investigator | Value of $k$ | Value of $k$ ($h^{-1}$) | Reference |
|---|---|---|---|---|
| 1 | Pangavhane et al., 1999 | – | 0.0392–0.5091 | [33] |
| 2 | El-Ghetany, 2006 | $2.95195 \times 10^{-5}$–$2.85679 \times 10^{-5}$ $s^{-1}$ | 0.10284–0.10627 | [37] |
| 3 | El-Sebaii et al., 2002 | $9.24 \times 10^{-6}$ $s^{-1}$ | 0.033264 | [48] |
| 4 | Kassem et al., 2011 | 0.00093 $m^{-1}$ | 0.0558 | [49] |
| 5 | Tiris and Ozbalta, 1994 | $7.53 \times 10^{-6}$ $s^{-1}$ | 0.027108 | [50] |
| 6 | Karathanos and Belessiotis, 1999 | – | 0.0106 | [51] |
| 7 | Zomorodian and Dadashzadeh, 2009 | – | 0.0808; 0.0795 | [52] |

## 8. Variation of drying rate constant with different parameters

The drying rate constant ‘$k$’ is the most suitable quantity for purposes of design, optimization and in situations wherein a large number of iterative model calculations are required. This stems from the fact that the drying rate constant embodies all the transport properties into a simple exponential function, which is the solution of the equation $dM/dt = -k(M_t - M_e)$ under constant air conditions. On the other hand, the classical partial differential equations, which analytically describe the four prevailing transport phenomena during drying (internal–external, heat-mass transfer), require a lot of time for their numerical solution and thus are not attractive for iterative calculations. The drying rate constant depends on both material and air properties as it is the phenomenological property representative of several transport phenomena. So, it is a function of material moisture content, temperature, size, as well as air humidity, temperature and velocity [9].

Notable results obtained by some of the investigators from their experimental work which substantiate the statement that the value of drying rate constant is dependent on the properties of the material to be dried as well as the drying air are summarized below:

Karathanos and Belessiotis, 1999, worked on drying of currants, grapes and plums. The drying rate constants for all the three products varied between 0.0138 and 0.0087 $h^{-1}$. Drying rate constant was found to be higher in currants and decreased in the following order $k_{currants} > k_{grapes} > k_{plums}$. Reason for the above relationship may be attributed to the nature of the agricultural products and to the initial pretreatment. Among the three products, skin of currants was the thinnest (1–5 μm), followed by skin thickness of grapes (10–30 μm) while the skin of plums was the thickest (about 50 μm) as measured by a micrometer. This is in accordance with the decreasing order of drying rate constant in currants, grapes and plums [51].

Barnwal and Tiwari ,2008, have found from their experimental results that the value of convective heat transfer coefficient of grapes dried in a greenhouse, with the grapes fully mature and ripe was found to be 0.45–1.21 W/m$^2$ K and for the grapes which were not fully mature and not completely ripe was 0.26–0.31 W/m$^2$ K. Hence, fully mature and ripe grapes got dried earlier than the grapes which were not fully mature and not completely ripe [30].

Azzouz et al., 2002, have found that the drying air temperature is an influential parameter in decreasing the drying time [35].

Hong-Wei Xiao et al., 2010, investigated the effect of different values of drying temperature and air velocity on the drying kinetics of grapes. Drying time required to reach the same final moisture content in grapes was 51, 45, 37 and 21 h. with a constant hot air velocity of 5 m/s at drying temperatures of 50, 55, 60 and 65 °C respectively. As the drying temperature is increased the drying time is reduced. Another drying experiment was carried out with a constant drying temperature of 60 °C with air velocities of 3, 5, 7 and 9 m/s the drying time required to reach the same final moisture content was 39, 37, 34 and 31 h. respectively. The effect of drying temperature on drying rate of grapes was more distinct than the effect of air velocity. This might be due to moisture diffusion from interior layer to grape surface is controlling the drying process and its rate mainly depends on drying temperature [40].

Pangavhane et al., 1999, investigated the effects of pretreatment on drying of grapes. Drying time required to reach the same final moisture content in grapes treated with five different pretreatment solutions was 8, 26, 27, 30 and 46 h. Drying rate constant obtained from all the five drying characteristics were 0.5091, 0.0852, 0.0767, 0.0615 and 0.0392 $h^{-1}$ respectively. Drying rate constant has the highest value with the lowest drying time and has the lowest value with the highest drying time. The value of drying rate constant ‘$k$’ increased with increase in drying air temperature [33].

Togrul and Pehlivan, 2004, have observed from their open sun drying experiments, that the drying rate of grapes decreased continuously with time and decreasing moisture content [43].

El-Sebaii et al., 2002, have established that there is a linear relationship between the drying rate constant ‘$k$’ and the drying product temperature when grapes are dried [48].

Bennamoun and Belhamri, 2006, while simulating the solar drying of grapes under variable external conditions have also found that the drying air temperature is an influential parameter. Increasing the air temperature provides the air more evaporative power as this is reflected in the drying time getting reduced. As confirmed by the experimental studies carried out by Togrul and Pehlivan, 2003, Azzouz et al., 2002, the drying air velocity is not as influential a parameter as the drying temperature and its influence decreases with an increase in the drying time [53].

## 9. Conclusion

The drying characteristics of grapes considered in this paper showed that the entire drying process occurred during a falling rate period. The climatic conditions like air temperature, humidity and solar radiation level affect the nature of the curve. Nature of curves in all the cases seem to decrease exponentially but the Logarithmic nature of curves may not be the same in all the cases.

Moisture ratio and drying time values when fitted into the exponential model gave the best fit. Results of the statistical analysis with high values of correlation coefficient and low values of standard error substantiate the fact that the exponential model can be used to describe the drying characteristics of seedless grapes. Further the exponential model was also found to satisfactorily describe the drying behavior of seedless grapes at different air velocities within a specific range of temperatures that are ideal for grape drying. Hence, it could be concluded that the exponential model could provide a good prediction of the drying characteristics of seedless grapes.

Values of log *MR* and drying time which were fit into the linear model using Curve Expert Version 1.3 gave ideal values of drying rate constant '*k*' which were quite similar to the values obtained experimentally by several investigators. Variation in the values of drying rate constant was due to variation in the initial moisture content of grapes, heating rate and temperature chosen for the drying process. Drying rate constant is a function of the variety and size of grapes, its moisture content as well as drying air temperature, velocity and humidity.

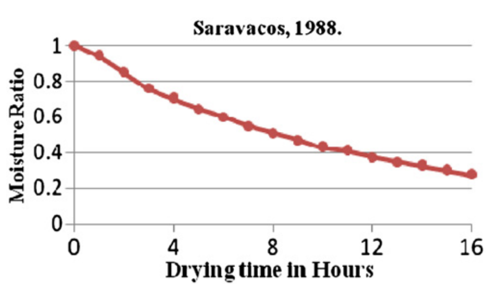


**Fig. 1.** Drying characteristics of pretreated grapes at air temperature of 60 °C with velocity 2 m/s.

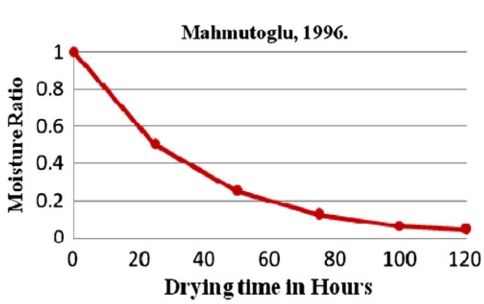


**Fig. 2.** Drying characteristics of pretreated grapes at air temperature 50 °C and velocity not mentioned.

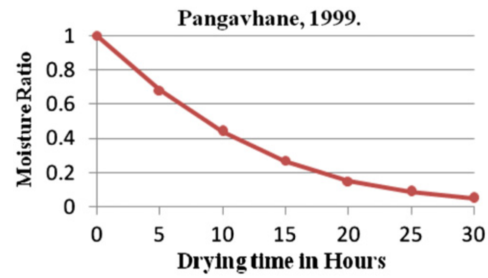


**Fig. 3.** Drying characteristics of pretreated grapes at air temperature of 60 °C with velocity 0.5 m/s.

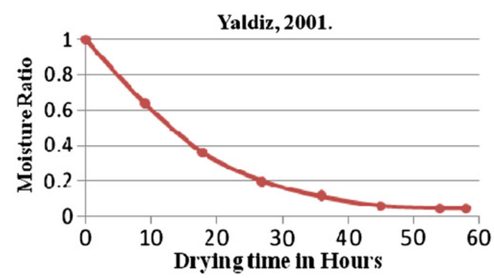


**Fig. 4.** Drying characteristics of pretreated grapes at air temperature of 39.6 °C with velocity 1 m/s.

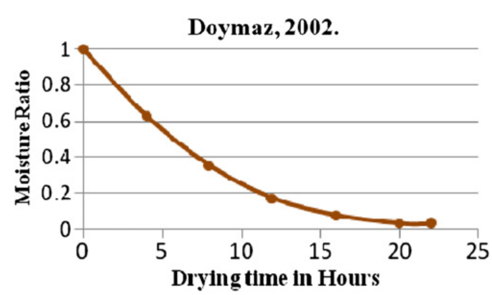


**Fig. 5.** Drying characteristics of pretreated grapes at air temperature of 60 °C with velocity 1.2 m/s.

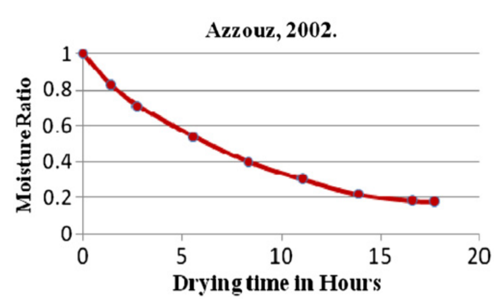


**Fig. 6.** Drying characteristics of pretreated grapes at air temperature 60 °C with velocity 0.5 m/s.

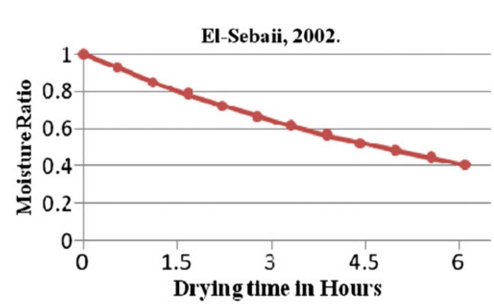


**Fig. 7.** Drying characteristics of pretreated grapes, air temperature and velocity not mentioned.

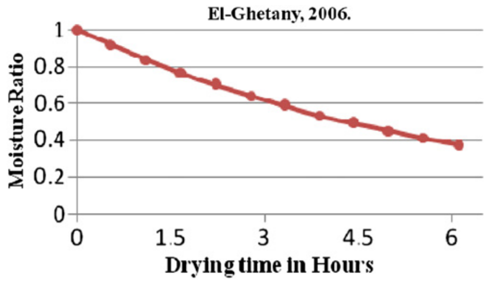


**Fig. 8.** Drying characteristics of pretreated grapes, air temperature and velocity not mentioned.

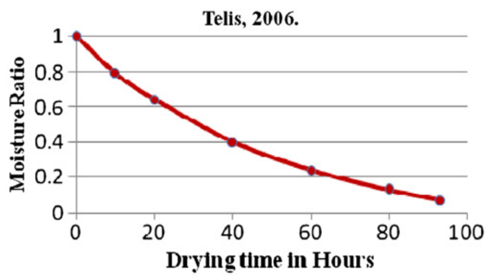


**Fig. 9.** Drying characteristics of pretreated grapes at air temperature 50 °C with velocity 1 m/s.

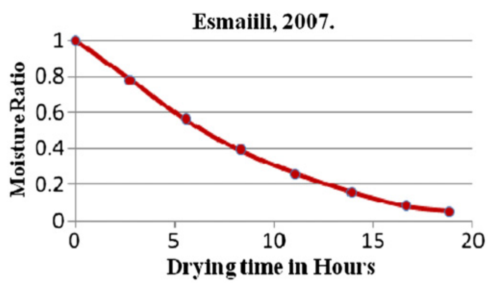


**Fig. 10.** Drying characteristics of pretreated grapes, air temperature and velocity not mentioned.

Hence, it could be concluded that the drying rate constant depends solely on the properties of the material to be dried as well as properties of the drying air.

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